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SIMMER ANALYSIS OF SRI HIGH PRESSURE BUBBLE EXPANSION EXPERIMENTS

by

P. E. Rexroth and A. J. Suo-Anttila*

ABSTRACT

SIMMER-II was used to analyze the results of the SRI nitrogen bubble expansion experiments. Good agreement was found for all of the experiments analyzed as well as the theoretical isentropic limiting case. Scaling to a full size CRBR reactor reveals no significant scaling effects for the structureless core.

I. INTRODUCTION

An important aspect in the study of core disruptive accidents (CDAs) in Liquid Metal Fast Breeder Reactors (LMFBRs) is an energetic disassembly of the core. Following the initial core motion leading to neutronic shutdown, the high-pressure two-phase fuel-steel mixture resulting from the disassembly expands, eventually imparting some of its energy to the sodium pool in the upper vessel. This sodium, in turn, could impact the head of the vessel.

The SIMMER computer program is a two-dimensional multifield, multicomponent, Eulerian fluid dynamics program which includes neutronics and energy and mass transfer treatments. The principle objective of SIMMER is to predict long term material motions, such as those described above, in disrupted LMFBR systems. One of the first applications of the SIMMER codes investigated the dynamics of postdisassembly expansions in the CRBR reactor. The analysis predicted substantial mitigation of system kinetic energy relative to ideal values. Los Alamos Scientific Laboratory has undertaken an experimental verification program to substantiate these results.

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Since mitigating effects can arise for two broad categories of phenomena, fluid dynamic effects and rate controlled exchange effects, the verification program has been organized to investigate these effects separately. A set of independent scaled, simulant experiments performed by SRI[1] appear to support these early analytical results. Analysis of these experiments with the SIMMER code is central to the program designed to verify the SIMMER energetics results for CRBR. The results of some of these analysis are presented here.

II. EXPERIMENT DESCRIPTION

The SRI experiments utilize a transparent 1/30 scale model of the CRBR vessel, as shown in Fig. 1. The removable upper core structure (UCS) and upper internal structure (UIS) are scaled to model the empty subassembly hex cans and the flow quide tubes, respectively. The bubble source material, room temperature nitrogen at 10 MPa in the experiments presented here, is released from the lower core into the water-filled vessel by an explosively driven, fast opening valve. As the bubble expands, it drives the liquid slug up to impact the vessel head. A pressure transducer at the vessel head records the impact pressure and a water surface gauge monitors the location of the upper surface of the pool.

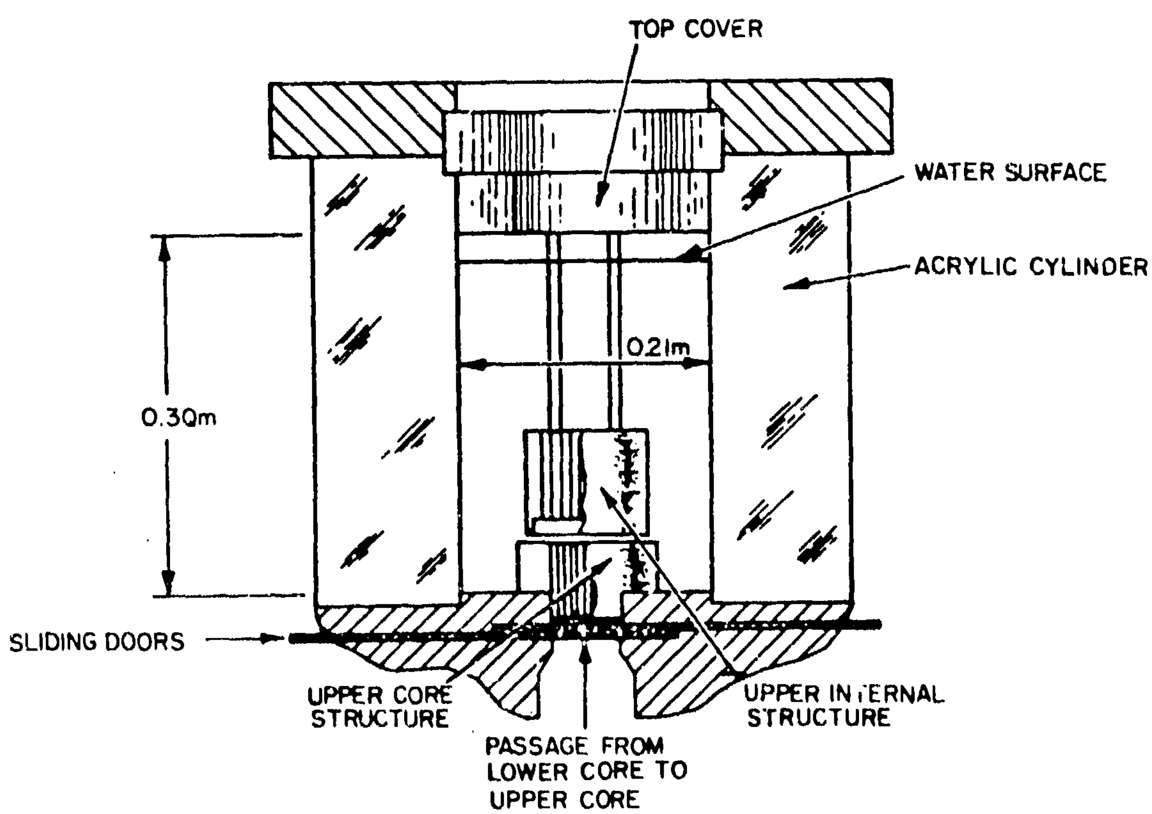

Fig. 1.
Experimental vessel.

Depending on the test, some combination of the following additional pressure gauges is included; at least one and in some cases two in the lower core, one at the edge of the upper core, and one suspended in the pool. Additional instrumentation includes high-speed (10,000 fps) motion pictures.

The geometric configurations as well as measured impact times and peak impact pressures for the five tests in this series are summarized in Table 1. The following important conclusions were drawn from these five experiments:

1. Even with no structure present, the kinetic energy of the liquid slug at impact was considerably less than that predicted from an isentropic expansion of the gas.

2. Presence of either the UCS or UIS or both delays the time of slug impact and diminishes the kinetic energy and peak pressure of the impact.

3. The UIS is more effective than the UCS in degrading the impact energy.

III. EXPERIMENT ANALYSIS

The primary goal of the analysis of these experiments was to see if SIMMER could adequately simulate the hydrodynamic behavior observed in the experiment, and to explain any significant discrepancies between experiment and calculation. Using the understanding gained from these calculations, it was hoped that the effects contributing to the degredation in system kinetic energy at impact as noted above could be identified. Finally, we wanted to determine whether or not similar effects could be expected to operate in the full scale reactor case.

TABLE I

SRI EXPERIMENTAL CONFIGURATIONS AND RESULTS

Test Number	Structure Present	Cover Gas Gap, mm	Impact Time, ms	Impact Pressure MPa
D-002	None	25.9	3.4	36.6
D-006	None	23.1	3.4	32.8
D-003	UCS	25.1	3.9	28.2
D-005	UIS	22.9	4.0	20.4
D-004	UIC & UCS	20.6	4.4	17.0

The calculational mesh used for the SIMMER simulation of test D-004 (UCS and UIS) is shown in Fig. 2. For the other cases, the appropriate structure is replaced by water. The variable mesh capability of SIMMER allows for accurate modeling of the experimental dimensions.

The sliding doors of the experiment are initially modeled as low density solid structure. In the experiment there are two overlapping doors, so that there is no communication between the lower and upper cores until 1.1 ms into the experiment. The calculations thus begin at 1.1 ms when a heat source is applied to the doors. The spatial and temporal heat distribution is such that the doors melt out at the same rate that the doors in the

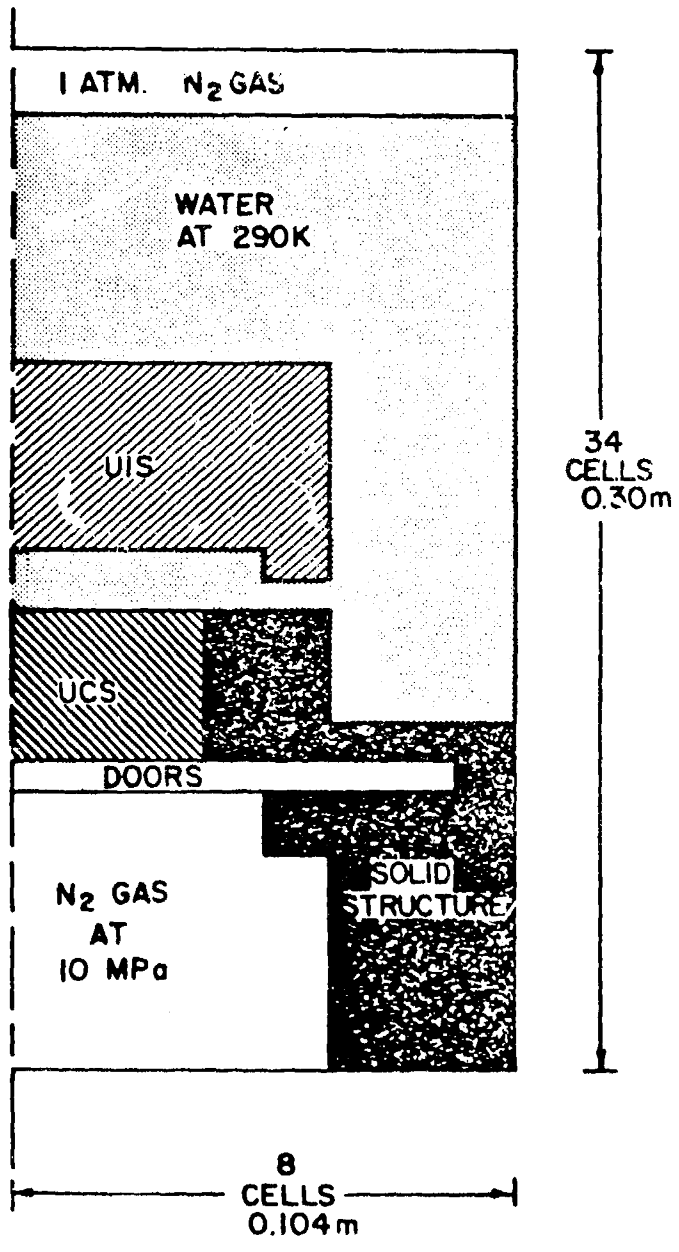

Fig. 2.
Calculational mesh.

experiment slide out. Upon melting, the door material becomes water, which having a density much greater than that of the structure, occupys a negligible volume. The effect is to create an empty cavity. Earlier calculations were performed in which the doors were assumed to be entirely open from the start. This instantaneous opening of the doors resulted in a steeper drop in lower core pressure than was recorded in the experiment. Inclusion of the opening doors improved the correspondence between the calculation and experiment considerably. Figure 3 shows the calculated lower core pressures for Test D-006 with and without the doors. Also included is the corresponding measured pressure.

SIMMER simulation calculations were performed for the four cases D-003 through D-006. D-002 was not done since the geometry was like that of D-006. The overall calculated fluid dynamic behavior in all cases was very similar to that observed in the experiments. A summary comparing calculated and experimental values for slug impact times and pressures is given in Table II. Also included is the calculated system kinetic energy at impact and the percentage of the isentropic energy (calculated assuming the doors open slowly). Note first, that the slug impact times agree to within 10%, leading credence to the SIMMER hydrodynamic treatment. The calculated pressures and kinetic energies also reflect the trend that both the UCS and UIS are active in mitigating the impact and that the UIS is the more effective. All calculated impact times are greater than those observed experimentally. Some small part of this effect may be due to imperfect simulation of the opening doors. A more significant contribution is believed to be a node size effect. As described later, use of a finer mesh decreases the calculated impact time.

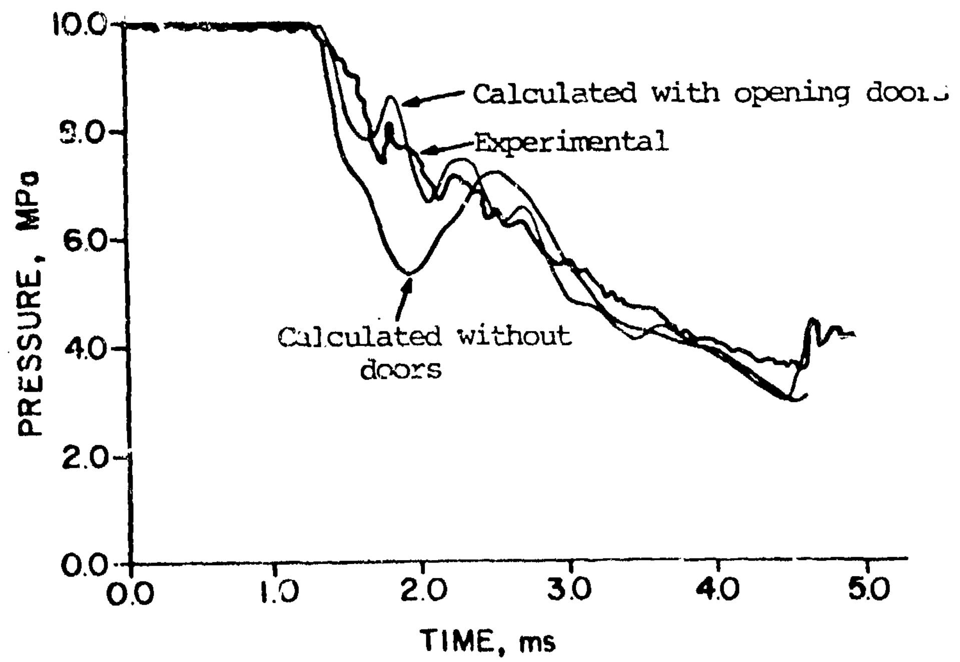

Fig. 3.
Calculated and experimental lower core pressures for D-006.

TABLE II

COMPARISON OF SIMMER CALCULATIONS AND EXPERIMENTAL RESULTS[a]

Test Number	Structure Present	Impact Time, ms	Impact Pressure MPa	Impact Kinetic Energy, kJ	% of Isentropic Impact Energy (Lower Bound)
D-006	None	3.5 (3.4)	57.5 (32.8)	2.75	83%
D-003	UCS	4.0 (3.9)	51.7 (28.2)	2.03	61%
D-005	UIS	4.3 (4.0)	37.1 (20.4)	1.43	43%
D-004	UCS & UIS	4.4 (4.0)	35.4 (17.0)	1.27	38%

[a]Figures in parenthesis are experimental results.

The excessive computing time required to run all problems with the fine mesh was not felt justified since the general flow behavior was not significantly different from the courser mesh case.

The calculated impact pressures are consistently higher than those measured. Most of this effect is due to the fact that as the cover gas compresses, the top mesh cell becomes nearly filled with liquid. A cell that is less than 3% vapor is treated as a single-phase liquid cell, so a water hammer effect results. An additional increase in calculated impact pressures is expected because the upper boundary used in the SIMMER calculation is rigid. The elastic, aluminum head used in the experiment, has the effect of moderating the measured pressure.

The calculated flow velocities and flow patterns were studied to determine why the structures had such a marked effect on impact times and energies. It was found that the UCS had the effect of simply throttling the flow. The flow area of the UCS and the pressure drop across it is simply not great enough to allow the mass flow rate that was achieved without the structure. In order to determine whether or not friction on the structure wall contributed to the throttling, the D-003 case was run with vapor and liquid minimum friction factors cut by an order or magnitude. This had virtually no effect on impact time and energy. The effect of the UIS in delaying impact could be seen both from the experimental movies and the flow maps generated from the SIMMER calculations. The UIS diverts the flow radially and degrades the axial velocity of the liquid-plenum interface.

An analysis of the partition of energy in the SRI experiments was performed to explain why the kinetic energy in the water slug falls short of the theoretical isentropic kinetic energy limit. In addition to the SRI D-006 experiment, one other case was analyzed to show how these effects can be reduced.

If the expansion were purely isentropic, then the work done by the gas in the core and the resulting kinetic energy of the slug can be calculated from the first and second laws of thermodynamics. The high pressure gas in the core will do expansion work upon the water slug according to the formula

$$W = \frac{P_2V_2 - P_1V_1}{1 - \lambda} \quad , \qquad (1)$$

where

w = work done, Joules,

P = Pressure, Pascals,

V = Volume, cubic meters,

λ = specific heat ratio, 1.4 for nitrogen, and

the subscripts 1 and 2 refer to initial and final conditions.

As the water slug moves upward, it does compression work upon the cover gas. The point at which the water slug has its maximum kinetic energy is where the decompressed core pressure is equal to the compressed cover gas pressure. The relationship for isentropic variations in pressure with respect to changes in volume is

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\lambda} . \tag{2}$$

Equation (2) applies to both the core and the cover gas. The volume change at which the core pressure equals the cover gas pressure can be found iteratively assuming that equal volumetric displacement occurs in both the cover gas and the core.

The sliding doors present a problem because they open at a rate that the core gas can do some work upon them. Two limiting cases present themselves. In the first case, the doors can be assumed to open instanteously resulting in a void that the gas will occupy isothermally. In the second limiting case the doors open slow enough that the gas will do work upon them, resulting in an isentropic expansion into the void. Thus the maximum possible isentropic kinetic energy has both an upper and lower bound depending upon the door opening behavior. Table III gives the results for the isentropic analysis of the SRI D-006 experiment.

To simplify the SIMMER energetics calculations the sliding doors have been removed altogether and the core gas has been allowed to fill the void isothermally. (Note that this was not the case with the experiment analysis runs where the doors were melted out).

Table IV gives the results of the SIMMER-II analysis of the SRID-006 experiment. As can be seen only 82.5% of the maximum possible kinetic energy is developed. An analysis of the pressures and temperatures of the core and expanded bubble reveals that a significant pressure gradient exists. This gradient prevents all of the potential energy of the gas from being converted into kinetic energy.

The magnitude of the pressure gradient is shown in Fig. 4. Shown is the pressure distribution along the verticle axis of the experimental vessel at the time of head impact.

As can be seen, there exists both an overexpansion and an underexpansion when compared with the isentropic pressure level. This situation is intuitively obvious since for a given volume an underexpansion at one location implies an overexpansion at another in order that mass and energy be conserved. Lastly, a summation over the energies in the system indicates that the nitrogen has the additional energy stored as potential energy.

The pressure gradient between the core and the bubble is caused primarily by the inertia of the gas. In addition, an examination of the velocities within the core barrel indicates that the sonic velocity is closely approached hence compressible effects also play a role in limiting the flow rate.

TABLE III
ISENTROPIC ANALYSIS OF D006 EXPERIMENT

Initial Conditions:

Core Pressure	1.013×10^{7}
Core Volume	1.004×10^{-3}
Door Volume	3.004×10^{-4}
Cover Gas Volume	7.815×10^{-4}
Cover Gas Pressure	1.01×10^{5}

After expansion into door volume

	Case 1 Upper Bound Isothermal Expansion Into Door Volume	Case 2 Lower Bound Isentropic Expansion Into Door Volume
Core Pressure	7.09×10^{6}	6.930×10^{6}
Core Volume	1.305×10^{-3}	1.305×10^{-3}
Core Temperature	290	261

After Expansion to Maximum Kinetic Energy

	Case 1	Case 2
Core + Bubble Pressure	4.142×10^{6}	3.739×10^{6}
Core + Bubble Volume	2.032×10^{-3}	2.028×10^{-3}
Core + Bubble Temperature	242.9	218.8
Cover Gas Pressure	4.142×10^{6}	3.739×10^{6}
Cover Gas Volume	5.468×10^{-5}	5.882×10^{-3}
Cover Gas Temperature	840.3	816.1
Work Done by Core	4076	3654
Work Done on Cover Gas	371	354
Net Kinetic Energy	3705	3300

TABLE IV

SUMMARY OF ENERGETICS ANALYSIS

Case	Liquid Slug Kinetic Energy	Vapor Kinetic Energy	Time to Maximum Kinetic Energy (ms)	% Isentropic (3705 J) Upper Bound
Base case SRI D-006	2619	437	2.2	82.5%
High Core Temperature (5000 K)	3671	28	1.936	99.8%
Large Scale (CRBR)	70.4 MJ	12.5 MJ	66.1	82.7%

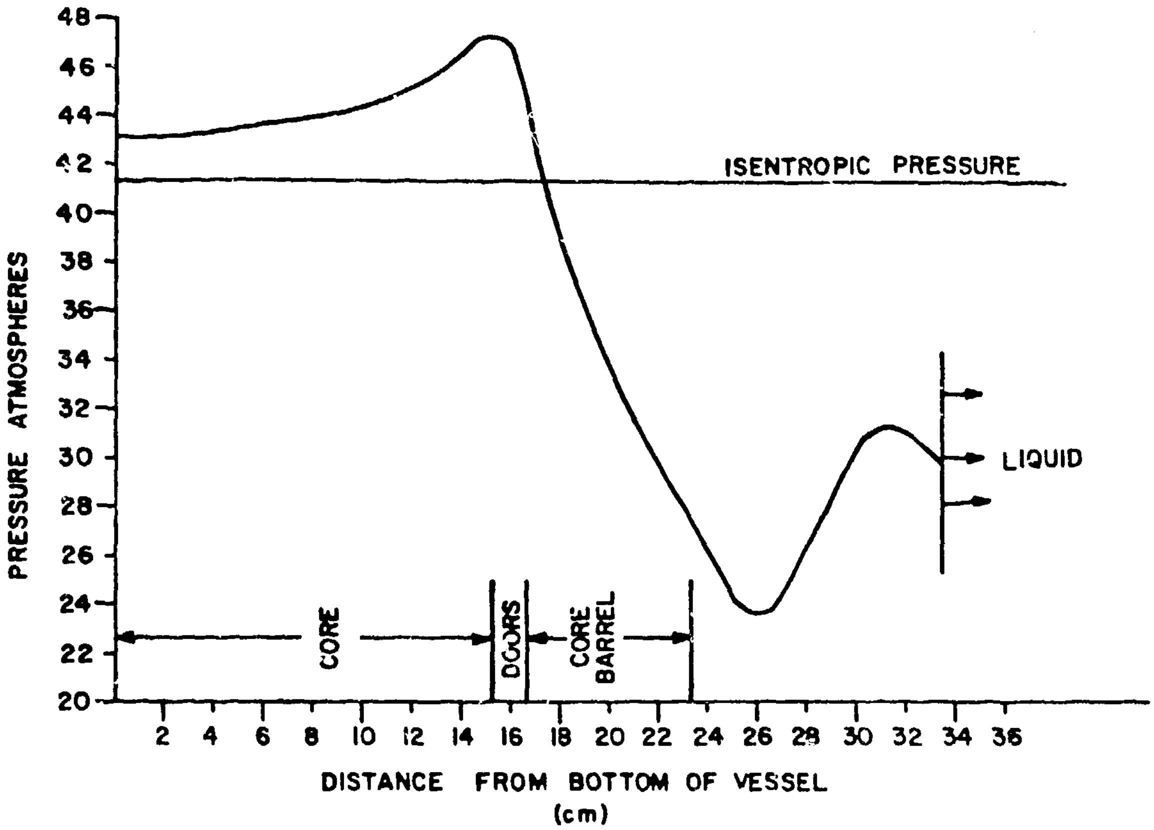

Fig. 4.
Bubble pressure distribution along the vessel axis.

If the core gas temperature is increased to 5000 K, and the initial pressure maintained, the gas density is greatly reduced and the sound speed is increased. This has the effect of eliminating virtually all of the nonisentropic effects. Thus a calculation of this type is useful in determining how well SIMMER can calculate the theoretical isentropic case and also to provide some measure of the accuracy of the SIMMER solutions.

In the present application, SIMMER is generating approximate solutions to the mass, momentum, and energy equations for two-phase hydrodynamic flow. The solutions are approximate because the equations are finite differenced and various combination of explicit and implicit methods are used in generating solutions. The error in these solutions can be reduced by using a large number of nodes and very short time steps. This approach was taken in calculating the isentropic hot core case shown in Table IV. This calculation utilized 1000 spatial nodes and time steps governed by a courant condition of 0.02. The result for this case is virtually exact, that is the total kinetic energy developed is 99.8% of the isentropic limit. An identical calculation with the standard mesh structure (272 nodes) yields a result with 8% less kinetic energy and a correspondingly later impact time.

For the calculations presented in this paper (except the hot-core isentropic) it can be assumed that the kinetic energies can be in error by as much as 8% and impact times correspondingly later.

The peak cover gas pressures do show less variation to node and time step size than does the kinetic energy, thus the peak cover gas pressures presented in this paper are representative of more accurate solutions.

It is of interest to see how well these experiments scale to a full size reactor. The results of the scaling analysis are also shown in Table IV for the 006 experiment. The results indicate that the D-006 structureless experiment scales very well with no significant differences in either hydrodynamics or energetics.

IV. CONCLUSIONS

The SRI nitrogen HCDA bubble simulation calculations were within 10% of the experimental values, and numerical effects were found to be primarily responsible for this difference. Overestimation of peak impulse pressures resulted from a water hammer effect which is an artifact of the calculation. The overall fluid motion calculated by SIMMER was very similar to that displayed by the SRI experimental movies. The discrepancies mentioned above did not have a significant effect on the overall calculated behavior of the system.

It was determined that the effect of the simulated upper core structure (UCS) in the experiments was to throttle the flow, slowing down the rate at which the bubble could form. The upper internal structure diverted flow radially, reducing, axial velocites, thus delaying impact and ultimate impact kinetic energy.

The primary cause of the nonisentropic behavior of the structureless D006 case was the existence of a pressure gradient between the lower core and the expanding bubble. A very high temperature case eliminated this effect and resulted in expected isentropic system kinetic energy.

Scaling to a full size CRBR reactor indicates that experiment D006 scales very well. No significant differences in either the hydrodynamics or energetics was found.

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REFERENCE

1. R. J. Tobin and D. J. Cagliostro, "Effects of Vessel Structures on Simulated HCDA Bubble Expansions," SRI Technical Report No. 5, Contract No. EY-76-C-03-0115 (November 1978).